M. Plum
13/Dec/01

Wire scanner and harp signal levels in the SNS

When an H^- beam strikes a wire the signal induced on the wire can be modeled by considering the H^- particle as a single particle entering the wire, whereupon it fragments into two electrons and a proton. Any electrons or protons that stop in the wire or exit the wire should be considered separately. The signal will thus comprise several sources: 1) the secondary electron emission (SEM) caused by the H^- particle entering the wire, 2) any electrons or protons that stop in the wire, and 3) SEM caused by any electrons or protons exiting the wire.

A well-known theory from Sternglass[1] describes the secondary emission yield as

$$Y = \frac{P d_s}{E_*} \frac{dE}{dx},$$

where Y is the secondary yield, P is the probability of an electron escaping, d_s is the average depth from which secondaries arise, E_* is the average amount of kinetic energy lost by the incoming particle per ionization produced in the target, and dE/dx is the stopping power of the target. Values for P, d_s, and E_* suggested by Sternglass are $P \approx 0.5$, $d_s \approx 1$ nm, and $E_* \approx 25$ eV. For a round wire the number of particles intercepted by the wire is calculated from the wire diameter, but the SEM signal is calculated from the wire circumference. The 1 nm thick layer of material just below the surface of the wire acts like an ion chamber that creates an electron for every 25 eV of energy loss within that layer.

The wire scanner signal computation therefore reduces to calculating stopping powers and ranges for H^- particles, protons and electrons. The H^- stopping power is the same as the proton stopping power for the very thin layer within the entering surface. It can be estimated from the Bethe-Bloch equation[2], and the proton range can be estimated by numerically integrating this equation. The electron range can be estimated with Feather's rule[3] suitably modified[4] for materials other than aluminum:

$$R(E) = 412\left(\frac{13}{27}\right)\left(\frac{A}{Z}\right)E^n \quad \left[\frac{\text{mg}}{\text{cm}^2}\right],$$

where $n = 1.265 - 0.0954\ln(E)$, A and Z are the atomic mass and number, and E is in MeV. The energy lost by the electron in the thin layer within the exiting surface of the wire can be estimated from the range equation. The above equations predict precise ranges for the electron and proton, but in reality there is straggling and scattering that leads to imprecision.

To further simplify our task we assume the wire has a uniform thickness given by the average thickness. For a wire diameter of D, the average thickness is $t = D^*\pi/4$. This assumption leads to further imprecision in the particle range and stopping power calculations. Sharp peaks that appear in the plots of signal vs. incident energy are in reality more rounded. I've written a Java program to calculate and plot the wire scanner signals as a function of H^- beam energy. Some results are shown in Figs. 1–10.

[1] E.J. Sternglass, Phys Rev **108**, 1 (1957). J.E. Borovsky and D.M. Suszeynsky, Phys. Rev. **A43**, 1416 (1991).
[2] See, e.g., Review of Particle Physics.
[3] Evans, "The Atomic Nucleus", McGraw-Hill, 1965.
[4] R.E. Shafer, "Comparison of H-minus and Proton Beam Heating in Thin Foils", 6/16/2000, SNS Tech Note SNS-104050000-TD0001 - R00.

Comparison with data
We can test our wire signal model by comparing predictions with actual measurements. As an example of such a measurement we take the case of H^+, H^0, and H^- beams at 800 MeV. These wire scanner measurements[5] were made at the LANSCE PSR with 100-micron SiC wires. The data showed that the ratio of the SEM coefficients for H^0:H^+ was 1.62, and the ratio for H^-:H^+ was 2.32. In comparison, the model predicts the H^0:H^+ ratio to be 1.62, and the H^-:H^+ ratio to be 2.23. The agreement is quite good.

A crude test of the energy dependence is found in the LANSCE wire scanner profiles for H^- beams between 100 and 800 MeV. These wires are all 127-micron (5-mil) diameter tungsten. The model predicts a fairly uniform response over this energy range, and rough (by eye) integrals of the areas under the profiles also show this characteristic. The available data are too noisy for a more quantitative comparison.

To test the absolute value of the model predictions we can compare to the LANSCE spallation target harp, which is uses a Phillips 7166H integrator CAMAC module to measure the charge from the 100-micron diameter SiC signal wires for a 250 ns beam pulse. The charge in the beam pulse, the beam profile, and the charge collected from the signal wires are all well known. From these parameters we find that the SEM coefficient is about 0.06 (it varies depending on how long the wires have been exposed to the beam – see below). To calculate the SEM coefficient for a wire with two elements (Si and C), we use the average atomic number (10), atomic weight (20), and ionization energy (138 eV), and the actual density (3.2 g/cm^3). The program predicts an SEM coefficient of 0.039, or about two thirds the measured value.

The program, although not yet thoroughly tested, thus predicts the correct signal ratios between H^+, H^0, and H^- beams, the correct energy dependence for H^- beams, and is a bit low on the absolute value for H^+ beams, although it is not surprising to miss on the absolute value given the variability over time of SEM coefficients (see below).

Errors and accuracy of calculations
SEM coefficients have been observed to change with time as target materials are exposed to beams. For example, Ferioli and Jung observed[6] a 50% decrease in the SEM coefficient for aluminum, gold plated aluminum, and gold plated titanium. Only small changes were observed for pure titanium. K.A. Brown et. al. observed[7] a 20% degradation (with no end in sight) for silver plated aluminum. I have observed about a 30% degradation (with no end in sight) for carbon-coated SiC wires used in the LANSCE spallation target harp. These examples serve to highlight the inherent inaccuracy in calculating SEM coefficients. The values predicted by the computer program should be given at least a ±50% error bar just for the degradation effect.

Additional error sources are in the approximations made by the program. The approximation that the wire has a uniform thickness, and the approximation that the H^-, proton and electron ranges are precise, lead to errors in the SEM coefficients for particles exiting the wire and to charge deposition in the wire. These effects will tend to smooth out the sharp peaks in the signal strength as a function of beam energy plots predicted by the program, and caution should be used when employing results in these regions.

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[5] M. Plum, "H^+, H^0, and H^- Secondary Emission Coefficients for 800 MeV beams," PSR Tech Note PSR-99-001, March 1999.
[6] G. Ferioli and R. Jung, "Evolution of the Secondary Emission Efficiencies of various materials measured in the CERN SPS secondary beam lines," Proceedings of the DIPAC 1997 conference, Frascati, Italy, 12-14 October 1997.
[7] K.A. Brown et. al., "Observations of Secondary Emission Chamber Degradation from Very High Intensity Proton Beams at the AGS," Proceedings of the 1997 Particle Accelerator Conference.

Predictions of signal levels in the SNS

Wire scanners and harps will be used at the SNS between 2.5 and 1000 MeV for H^- beams, and at 1000 MeV for H^+ beams. Wire types being considered include 32-micron diameter carbon, 25-micron diameter tungsten, 100-micron W-Re, and 100-micron SiC. In the linac the peak beam current (averaged over a minipulse) is 26 mA, and the beam sizes range from a low of 0.04 cm rms in the CCL to a high of 0.22 cm rms in the CCL and SCL. The RTBT extraction line will have peak currents (averaged over a 695 ns beam pulse) of 35 A. To simplify the presentation of the data we shall assume a 26 mA beam current and a 0.2 cm rms beam size. Results, shown in the following figures, for other beam currents and sizes can be scaled from these values.

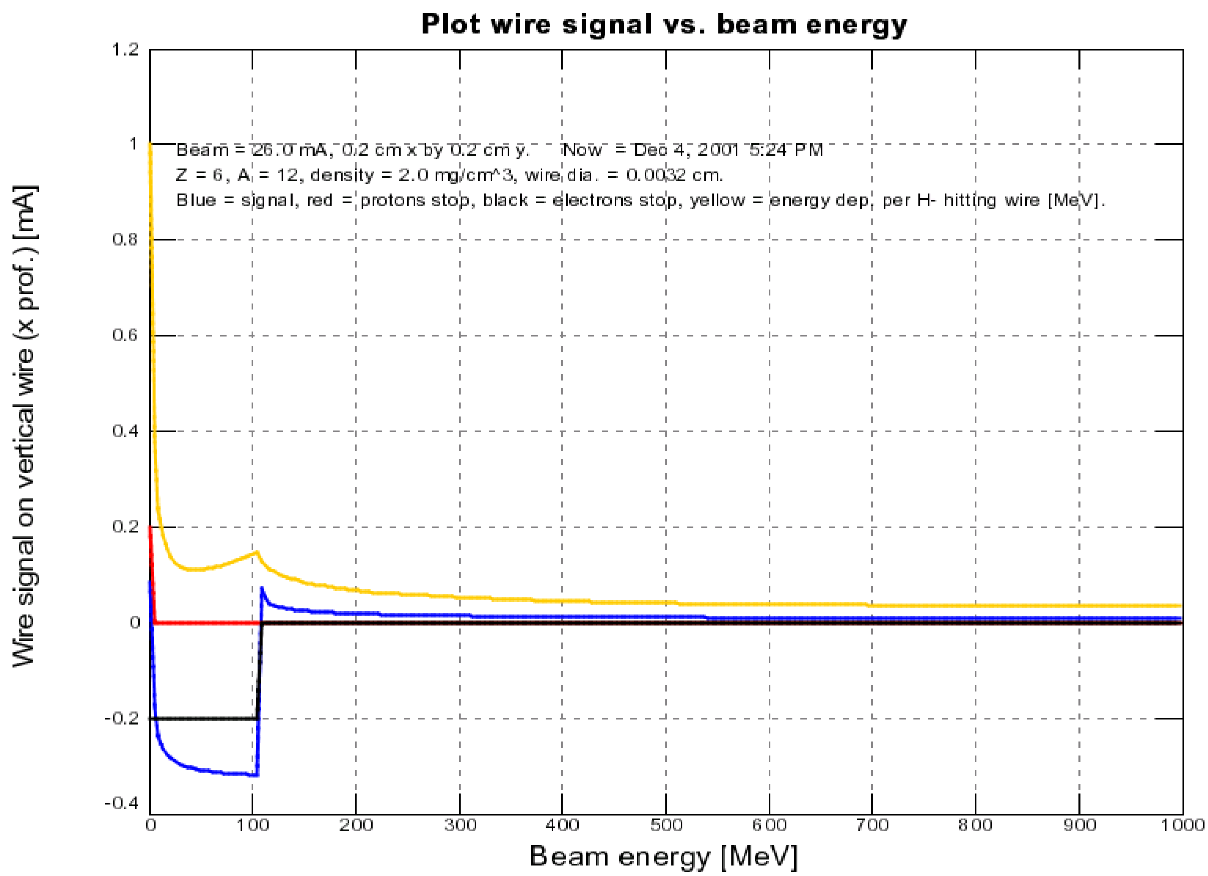

Figure 1. Carbon wire, 0.032 mm dia. The blue line is the wire scanner signal in units of mA. The red line, when non-zero, indicates that protons are stopping in the wire. The black line, when non-zero, indicates that electrons are stopping in the wire. The yellow line indicates energy deposited in the wire per H^- particle, in units of MeV. Note that above 20 MeV, the most wire heating occurs at about 108 MeV.

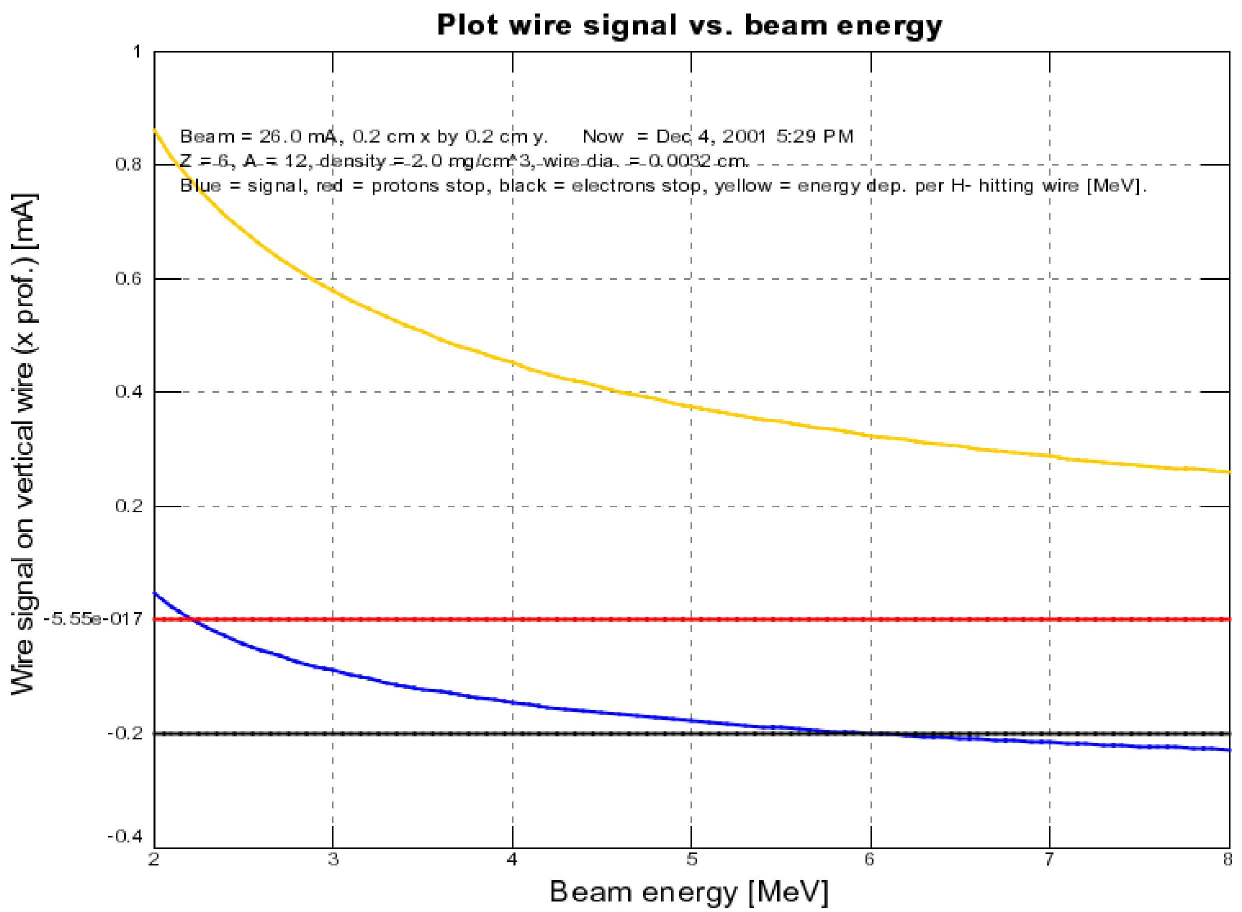

Figure 2. Carbon wire, 0.032 mm dia., detailed view of 2 to 8 MeV region.

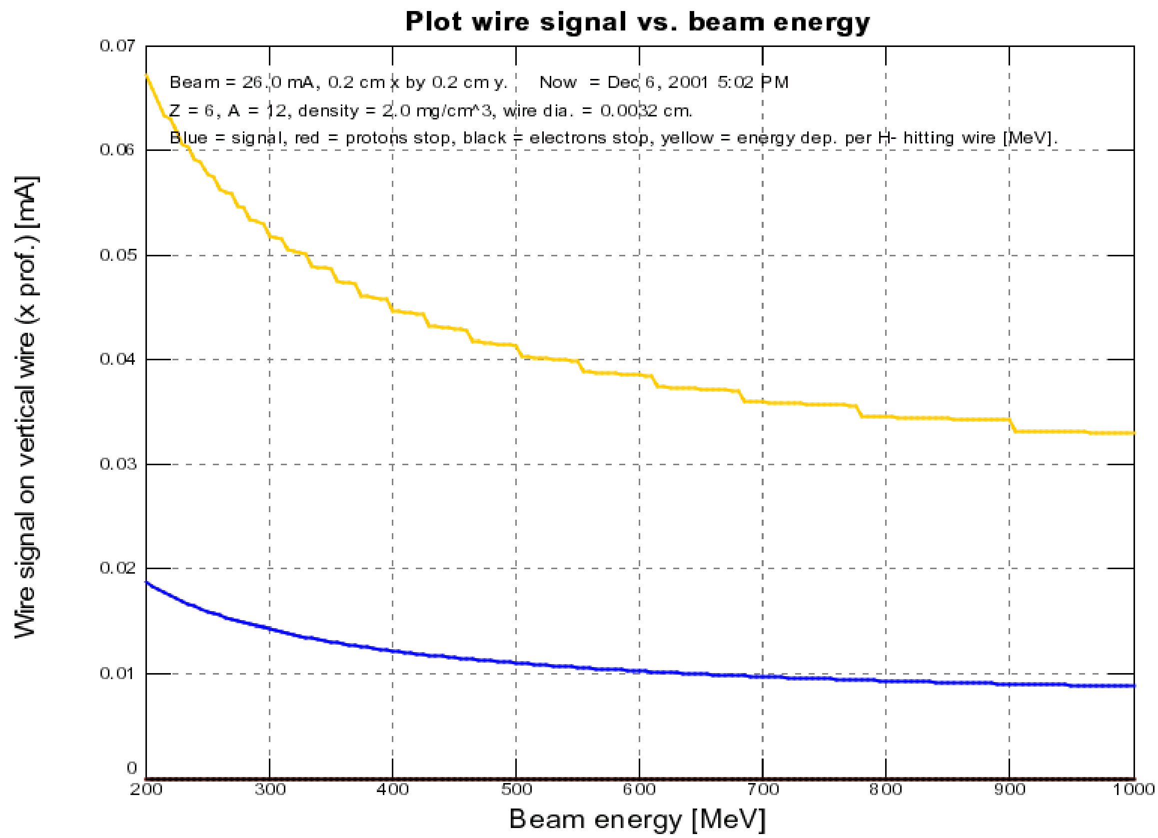

Figure 3. Carbon wire, 0.032 mm dia., detailed view of 200 to 1000 MeV region.

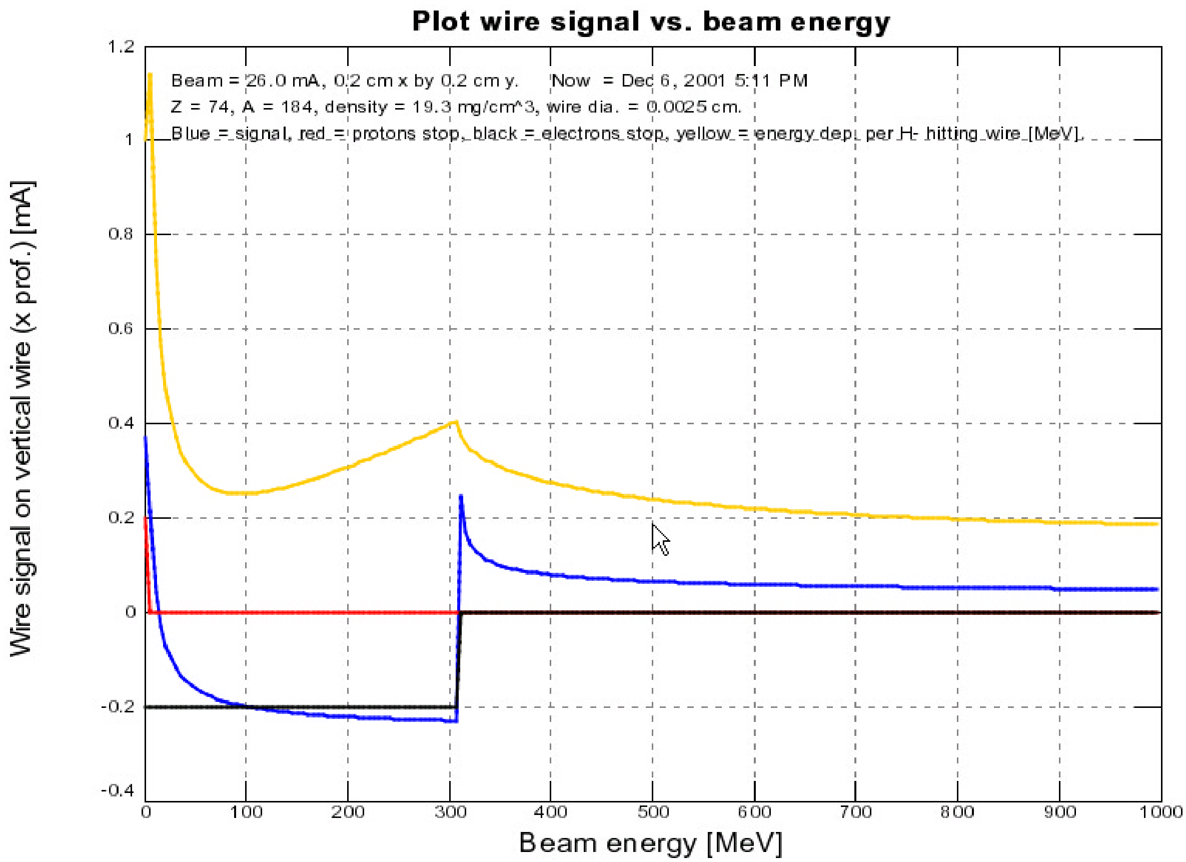

Figure 4. Tungsten wire, 0.025 mm dia. The blue line is the wire scanner signal in units of mA. The red line, when non-zero, indicates that protons are stopping in the wire. The black line, when non-zero, indicates that electrons are stopping in the wire. The yellow line indicates energy deposited in the wire per H^- particle, in units of MeV. Note that above about 25 MeV, the most wire heating occurs at about 310 MeV.

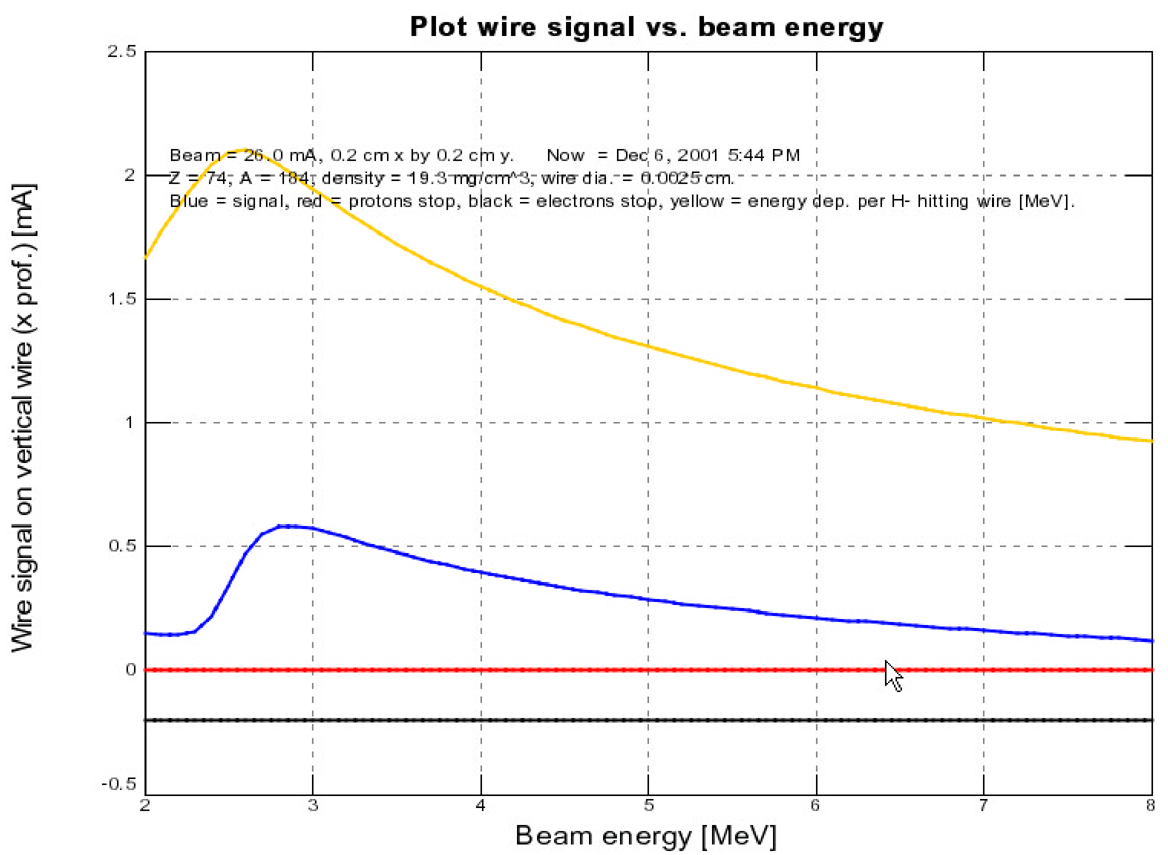

Figure 5. Tungsten wire, 0.025 mm dia., detailed view of the 2 to 8 MeV region.

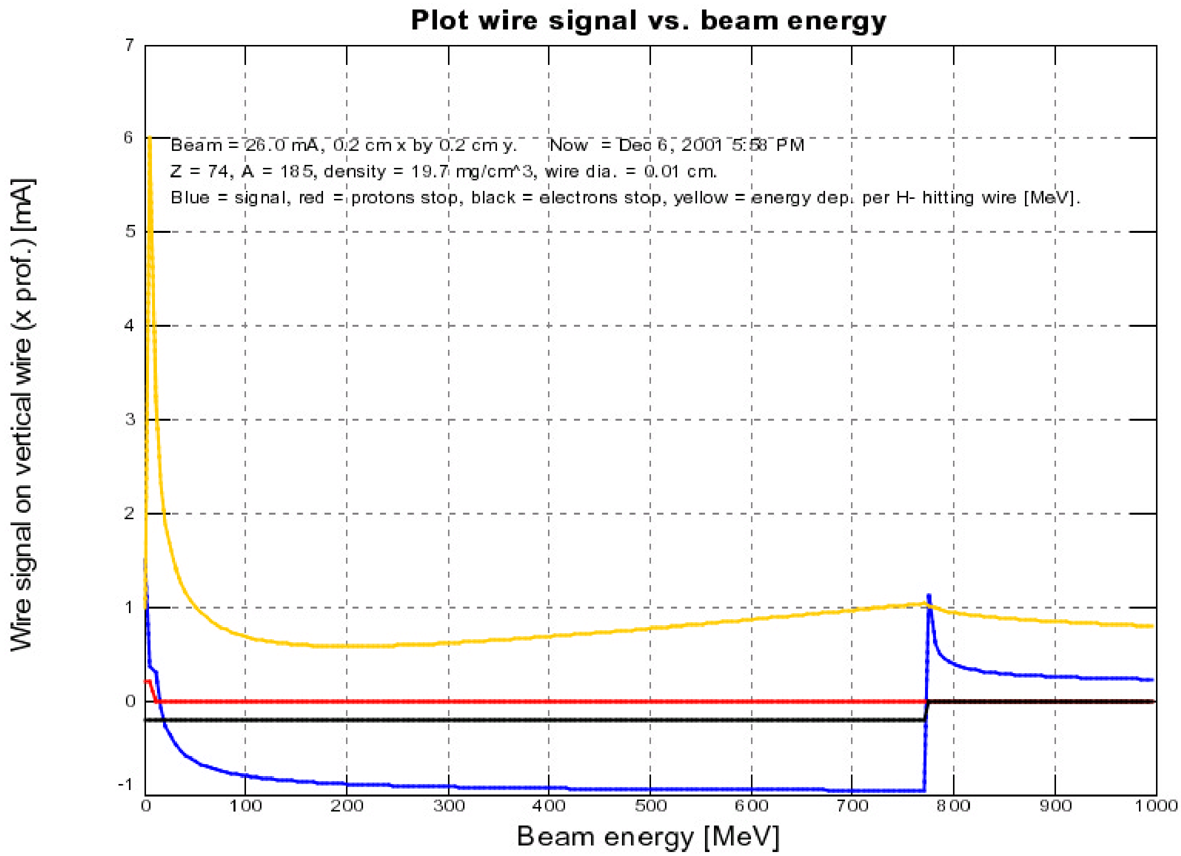

Figure 6. Tungsten-rhenium wire, 0.1 mm dia., (A = 185, Z = 74, I = 732 eV, ρ = 19.7 g/cm^3). The blue line is the wire scanner signal in units of mA. The red line, when non-zero, indicates that protons are stopping in the wire. The black line, when non-zero, indicates that electrons are stopping in the wire. The yellow line indicates energy deposited in the wire per H^- particle, in units of MeV. Note that above about 50 MeV, the most wire heating occurs at about 770 MeV.

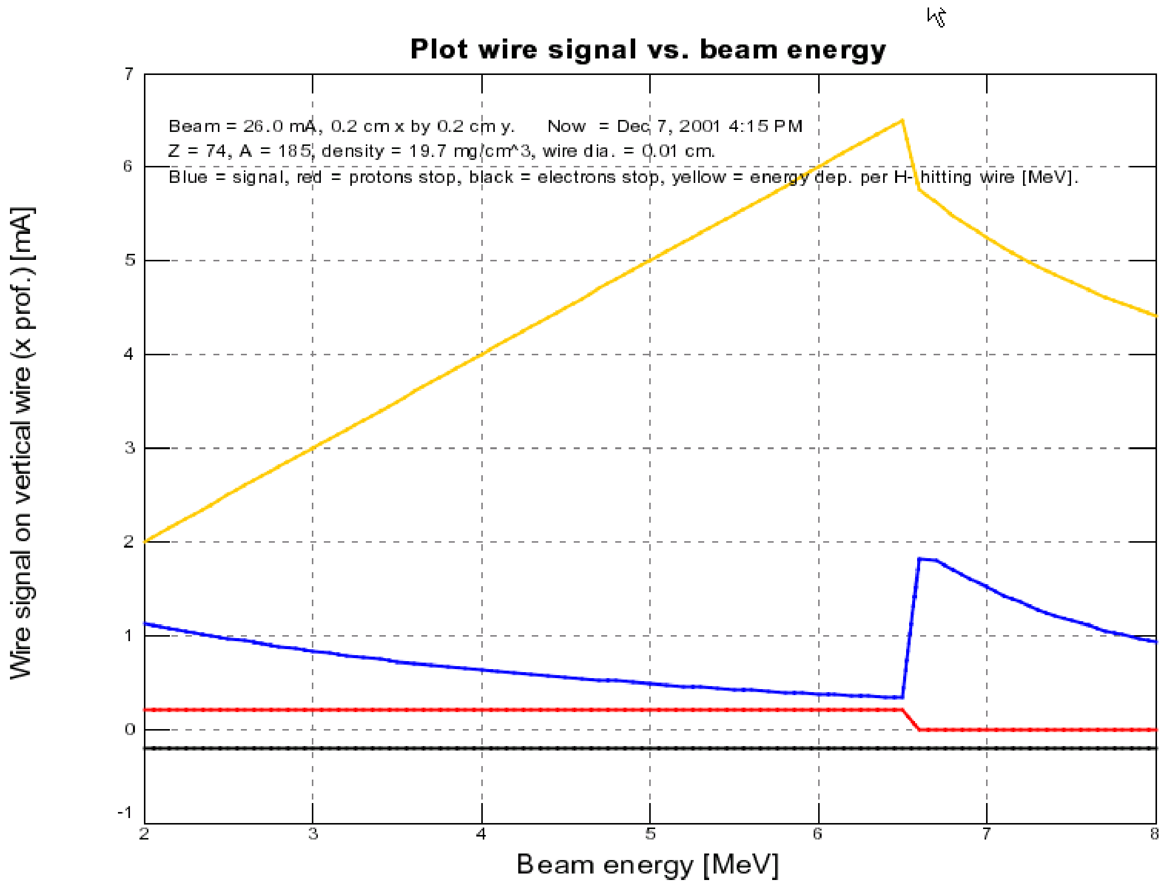

Figure 7. Tungsten-rhenium wire, detailed view of the 2 to 8 MeV region.

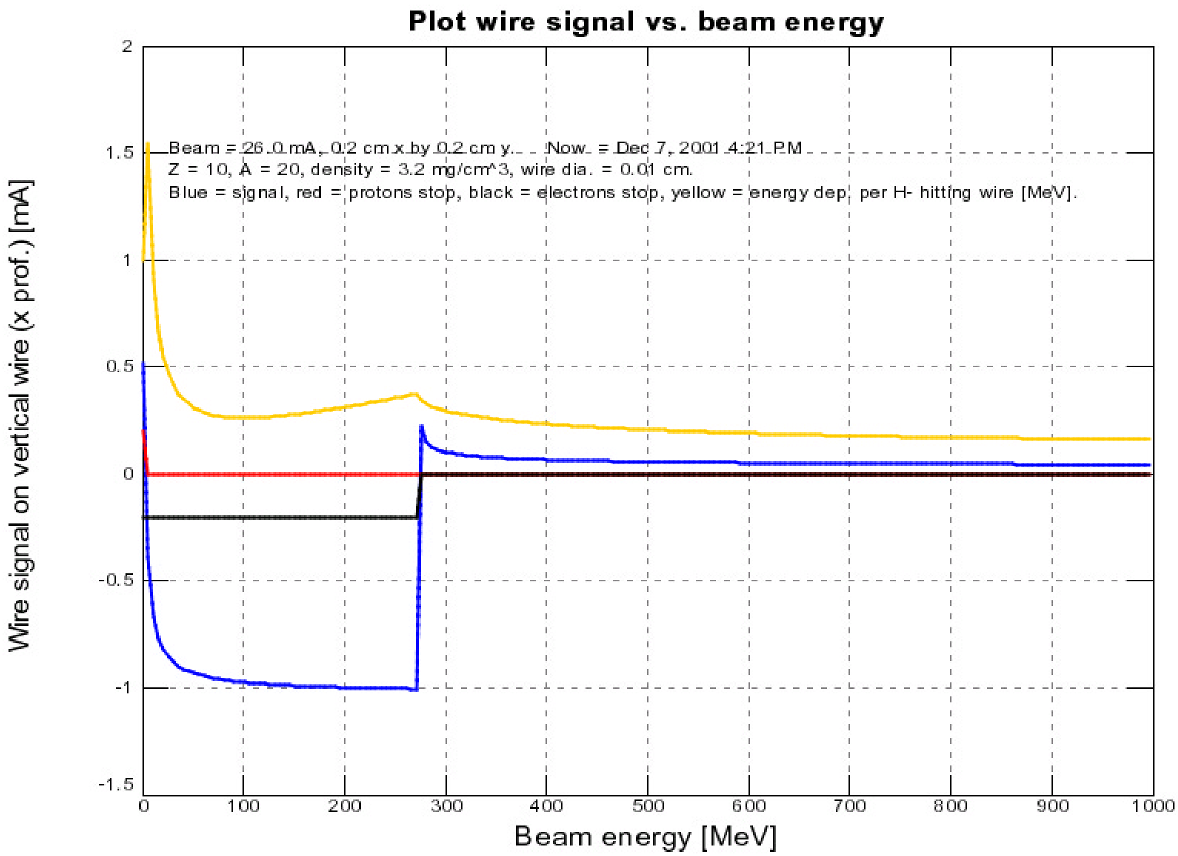

Figure 8. SiC wire, 0.1 mm dia. (A = 20, Z = 10, I = 138 eV, ρ = 3.2 g/cm^3). Detailed view of the 2 to 8 MeV region. The blue line is the wire scanner signal in units of mA. The red line, when non-zero, indicates that protons are stopping in the wire. The black line, when non-zero, indicates that electrons are stopping in the wire. The yellow line indicates energy deposited in the wire per H$^-$ particle, in units of MeV. Note that above about 25 MeV, the most wire heating occurs at about 270 MeV.

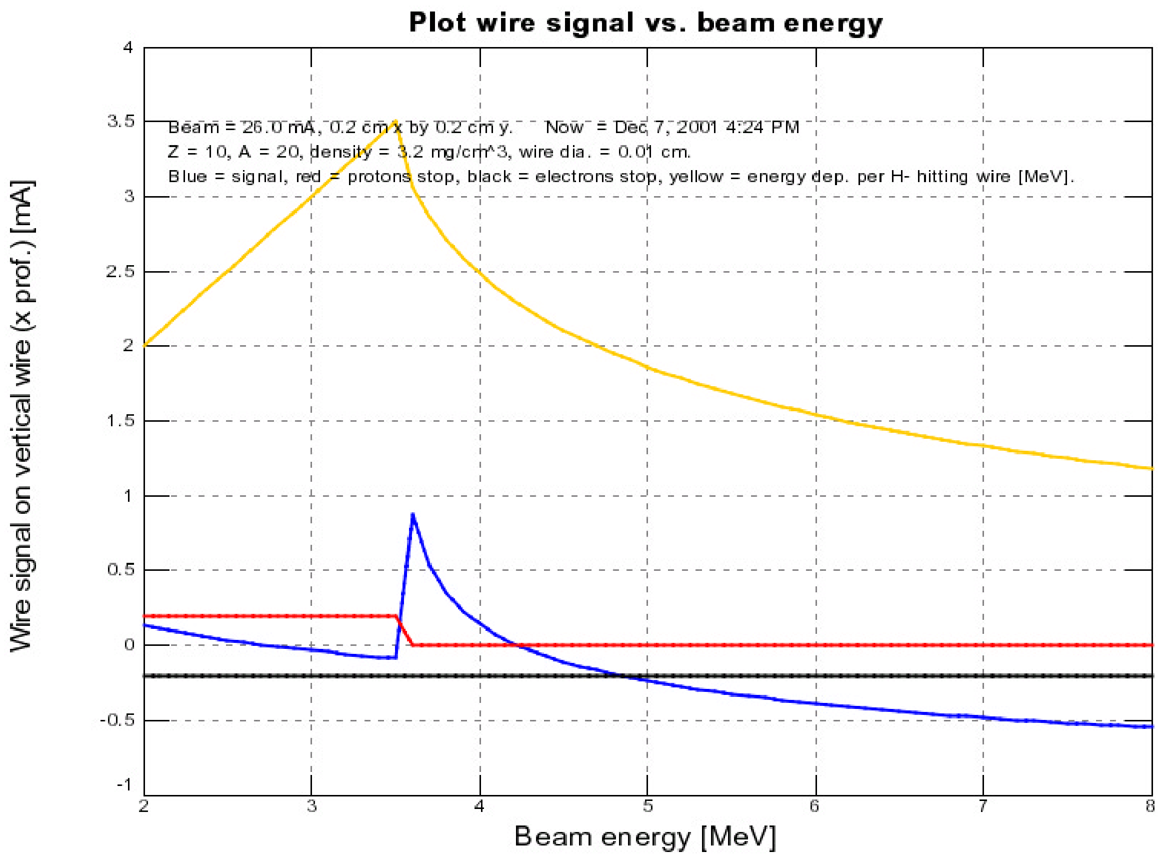

Figure 9. SiC wire, 0.1 mm dia., detailed view of the 2 to 8 MeV region.

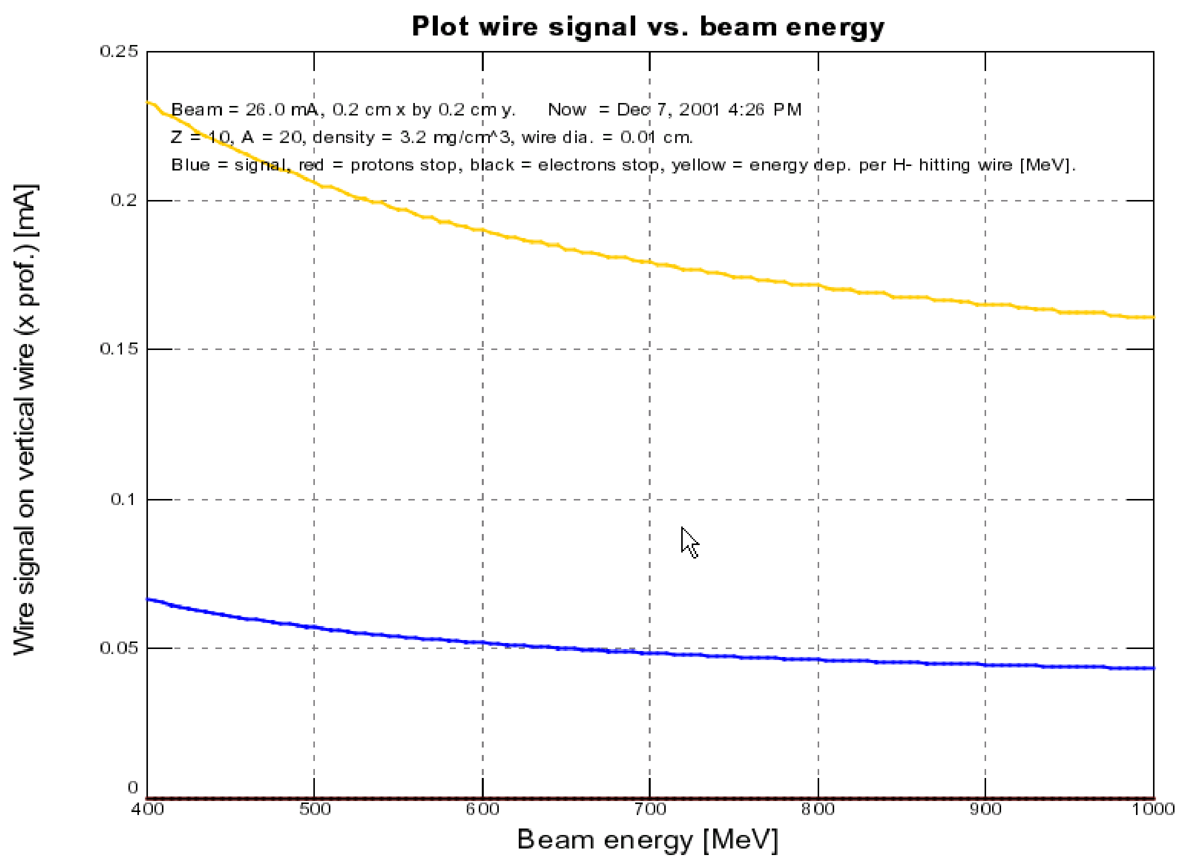

Figure 10. SiC wire, 0.1 mm dia., detailed view of the 400 to 1000 MeV region.